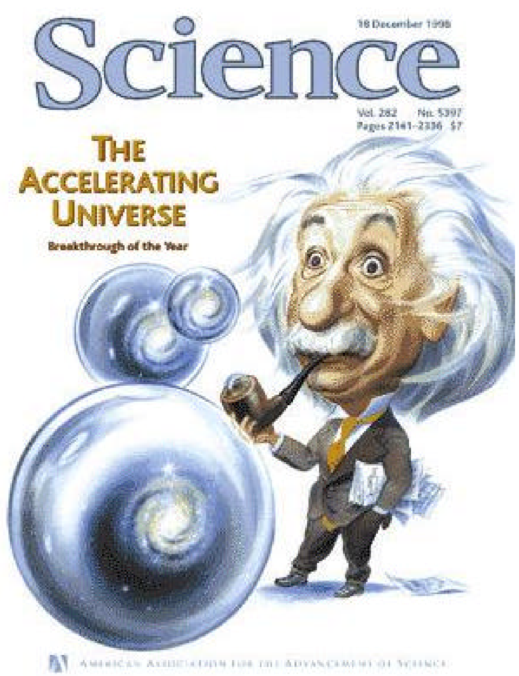
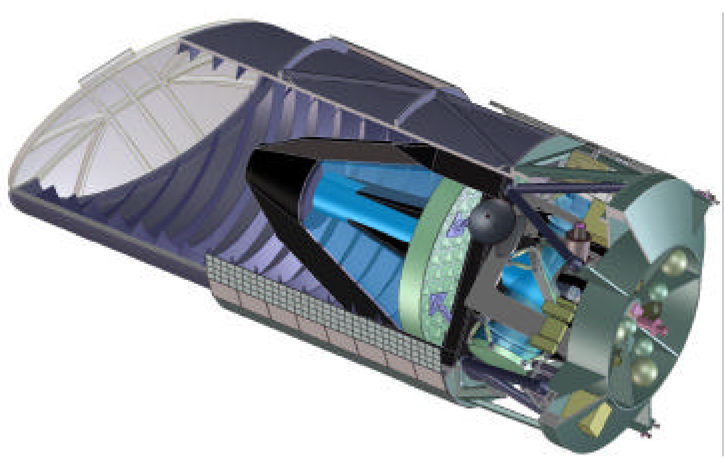
Dark Energy,

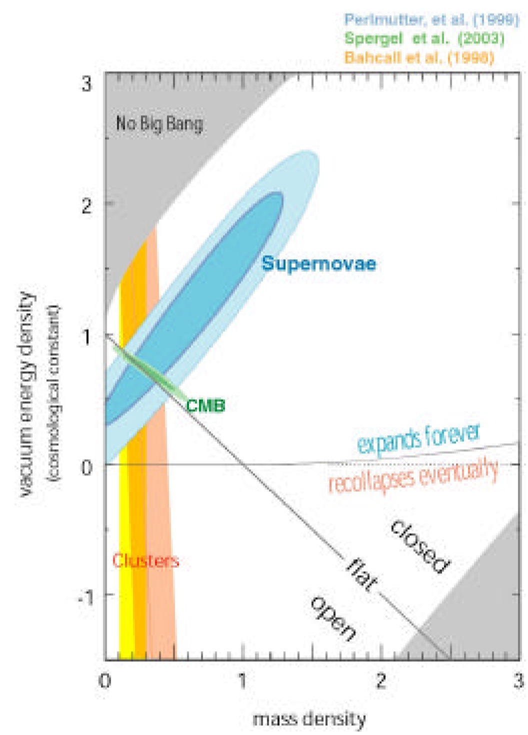
the Expansion History of the Universe,

and SNAP

Eric Linder
Berkeley Lab







Evidence for Acceleration

Supernovae Ia:

Ω_{DE} , w=p/ρ , w´=dw/dz

Observation -- Magnitude-redshift relation

Age of universe:

Contours of t_0 parallel CMB acoustic peak angle: t_0=13.7±0.2 Gyr

[*Flat universe, adiabatic perturbations*]

Knox et al. 2001
Spergel et al. 2003

CMB Acoustic Peaks:

Substantial dark energy, *e.g.* $\Omega_L = 0.73 \pm 0.04$

[*Small GW contribution, LSS, H_0*]

Bond et al. 2002
Spergel et al. 2003

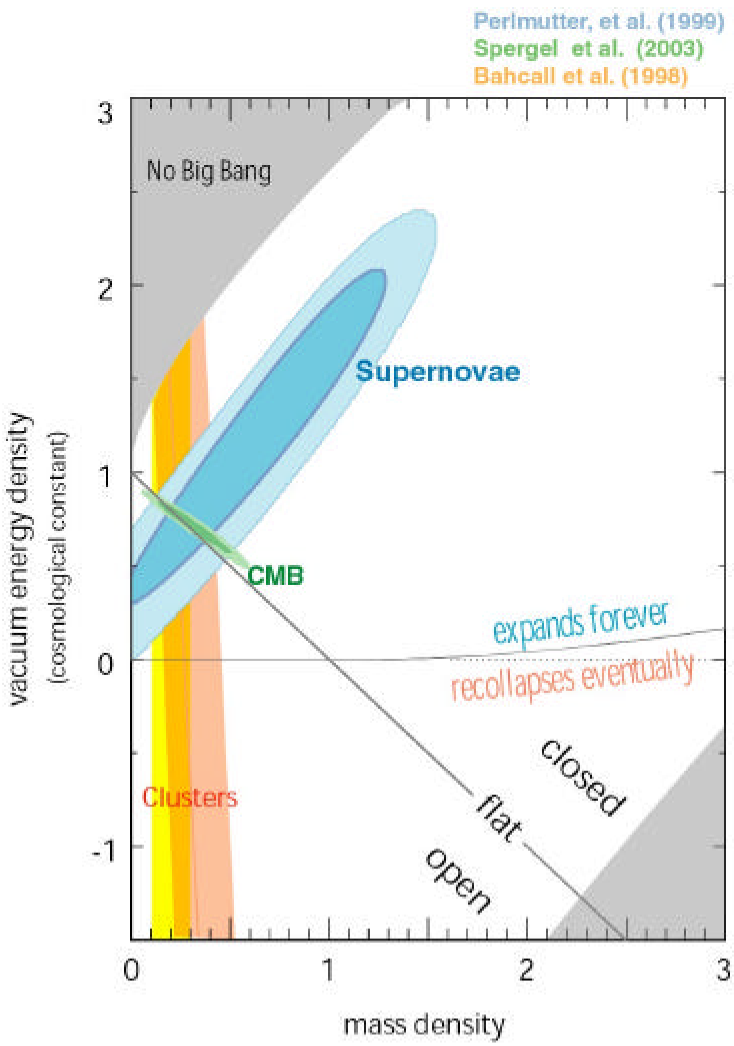
Large Scale Structure:

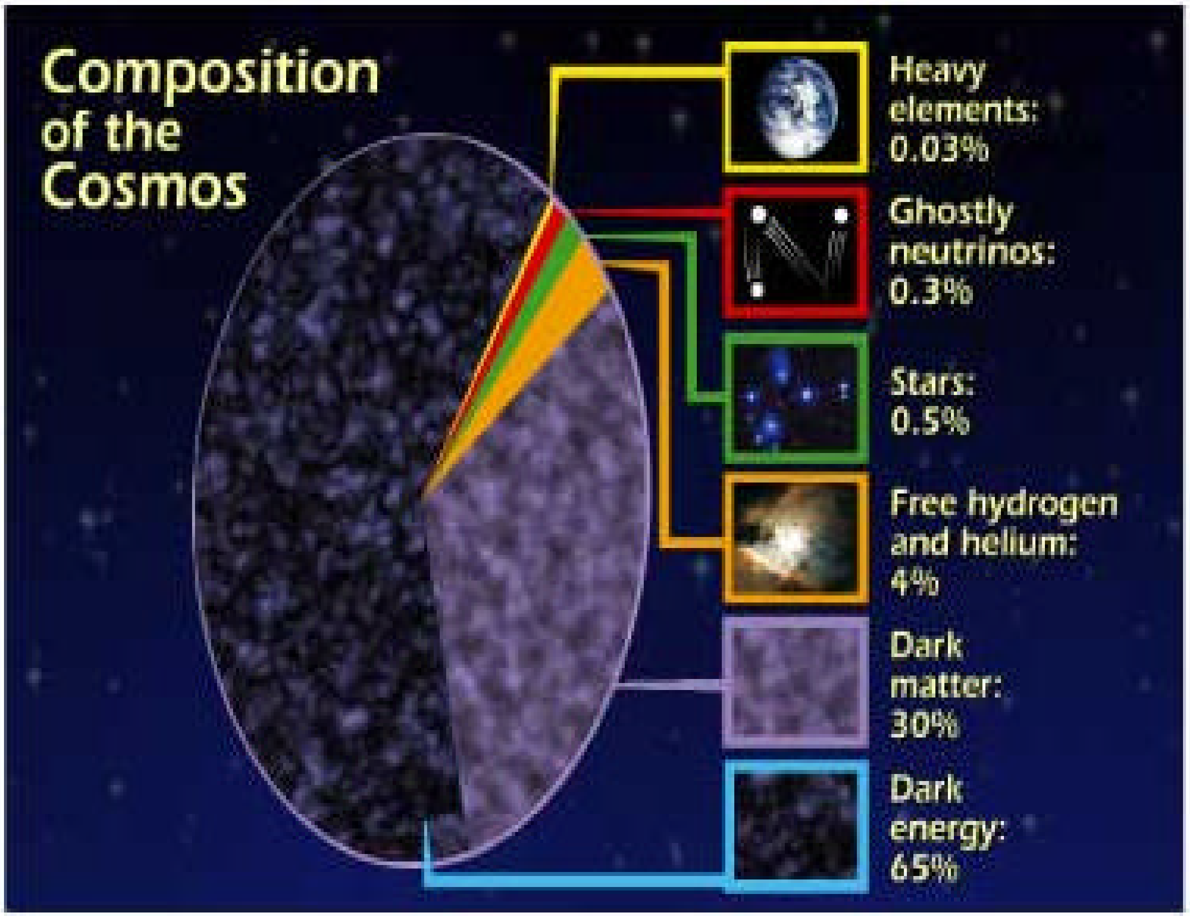
Power spectrum P_k, Growth rate, “looks”

[*simulations*]

Dark Energy

- Supernova data shows an acceleration of the expansion, implying that the universe is dominated by a new Dark Energy!
- Remarkable agreement between Supernovae & recent CMB and LSS results.





courtesy STScI

Dark Energy Theory

1970s – Why $\Omega_M \sim \Omega_k$?

1980s – Inflation! Not curvature.

1990s – Why $\Omega_M \sim \Omega_L$?

2000s – Quintessence! Not Λ?

Cosmological constant is an ugly duckling

Dynamic scalar field is a beautiful swan

Lots of theories, little data.

We want to say, for example:

2010: A dynamical scalar field with

equation of state today $w(z=0) \equiv w_0 = -0.82 \pm 0.05$

time variation of the EOS $dw/dz \equiv w' = 0.29 \pm 0.11$

consistent with Supergravity inspired field theories

L: Ugly Duckling

Astrophysicist:

Einstein equations –

$$\Lambda g_{ab}$$

® $\boxed{p = -r}$

Naturally, r =const= r_{PL}

$$\boxed{W_L = 10^{120}}$$

Today $W_L » W_M$

Field Theorist:

Vacuum – Lorentz invariant

$$T_{ab} \sim \eta_{ab} = \mathrm{diag}\{-1, 1, 1, 1\}$$

® $\boxed{p = -r}$

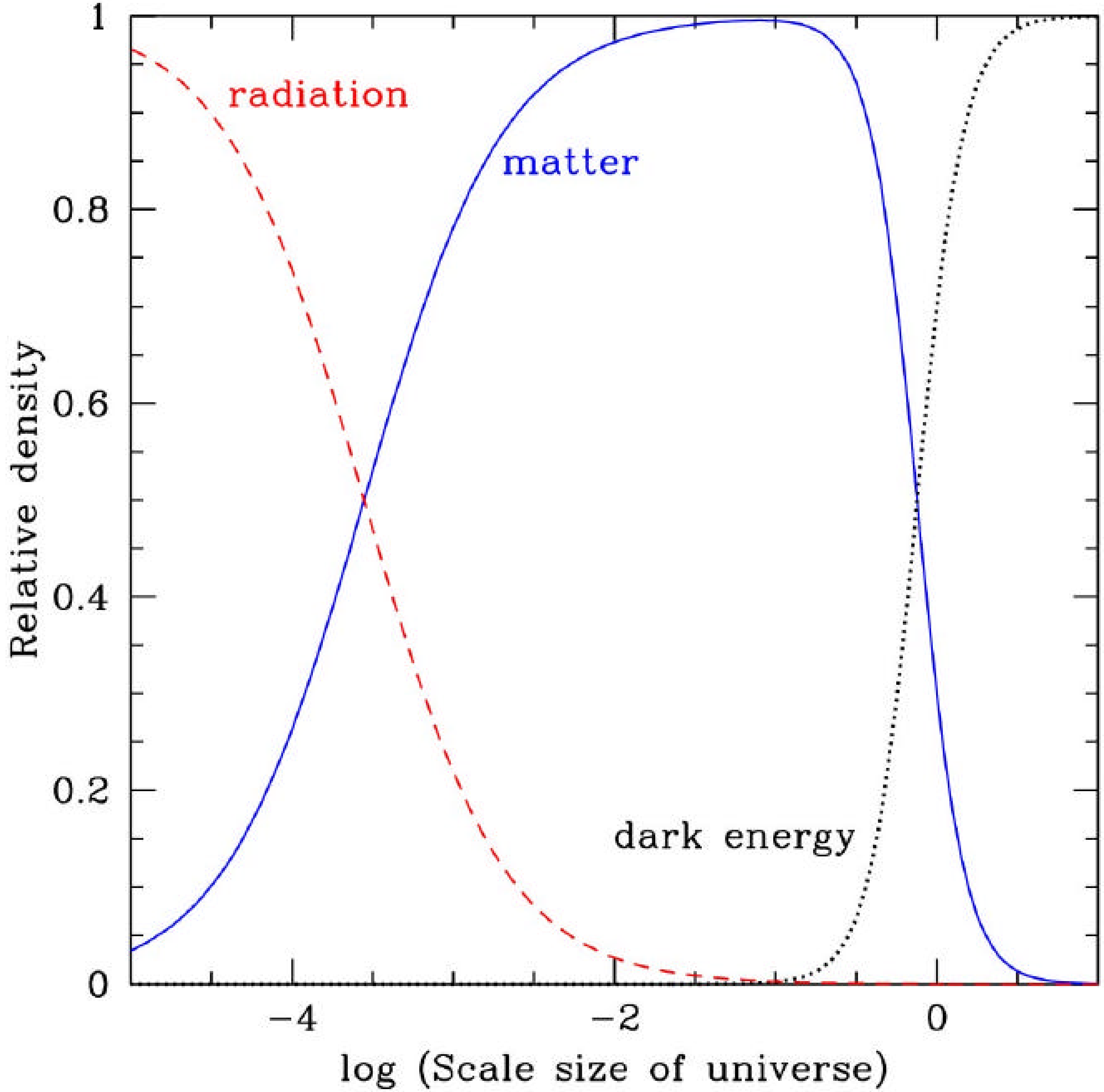
Naturally, $E_{vac} \sim 10^{19}$ GeV

$$E_L \sim \mathrm{meV}$$

$$\boxed{L = 0?}$$

- **Fine Tuning Puzzle – why so small?**
- **Coincidence Puzzle – why now?**

Why Now?


radiation
matter
dark energy
Relative density
0
0.2
0.4
0.6
0.8
1
−4
−2
0
log (Scale size of universe)

Scalar Field: Beautiful Swan

Dynamical Field

– explain coincidence, but not fine tuning

What is an equation of state?

$$dU = -p\, dV$$

1^{st} Law of Thermo

$$d(\rho V) = d\rho + \rho dV = -p\, dV$$

$V \sim a^3$

Equation of state $\boxed{w=p/\rho}$

$$w = \frac{K-V(\phi)}{K+V(\phi)}$$

$$\rho_\phi(a) = \rho_\phi(0)\, e^{-3\int d\ln a(1+w)} \sim a^{-3(1+w)}$$

but time variation $w' = dw/dz$ is a critical clue

What does negative pressure mean?

Consider a rubber band: $dU = +T\, dl$

Fundamental Physics

Astrophysics ® Cosmology ® Field Theory

r(z) ® Equation of state w(z) ® V(f)

SN
CMB
LSS

V (f(a(t)))

- Dynamical Effect on *a(t)* – clean and accurate
- Effect on growth rate of large scale structure – sensitive, but need to separate from astrophysics

Map the expansion history of the universe

Cosmological Probes

A handful of promising cosmological probes:
What are the systematics?

- **SZ Effect -- cluster counts**
  Projection effects
  Mass-temperature relation
  Limiting cluster mass
  needed better than 10% dex
  for 3 σ bias
- **SZ Effect with X-ray data -- angular distance**
  Clumpy electron medium, asphericity
  Cluster map resolution
- **Galaxy halo counts**
  Mass -- halo velocity profile relation
- **CMB**
  Weak dependence on w
  through ISW effect
  Cosmic variance
- **Weak Lensing**
  B modes not all zero
  Lensing model: NFW, SIS halos?
  Nonlinear part of power spectrum
  needed better than 5%
  for 1 σ bias
- **Strong Lensing**
  Lens mass distribution
- **Alcock-Paczynski Effect**
- **Peculiar Velocities**
- **Type Ia Supernovae**
  Evolution
  Extinction
  Gravitational Lensing

CfCP Dark Energy Workshop (Chicago,2001)

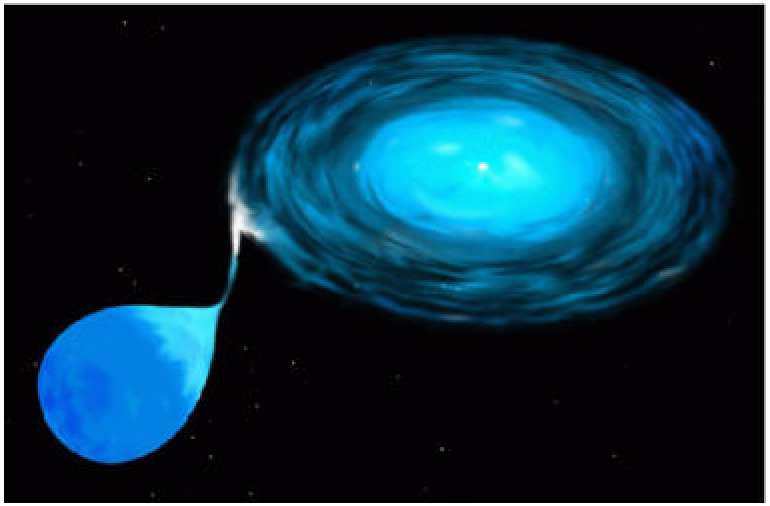
New large scale structure simulations with *w´* – Frenk, Jenkins, & Linder

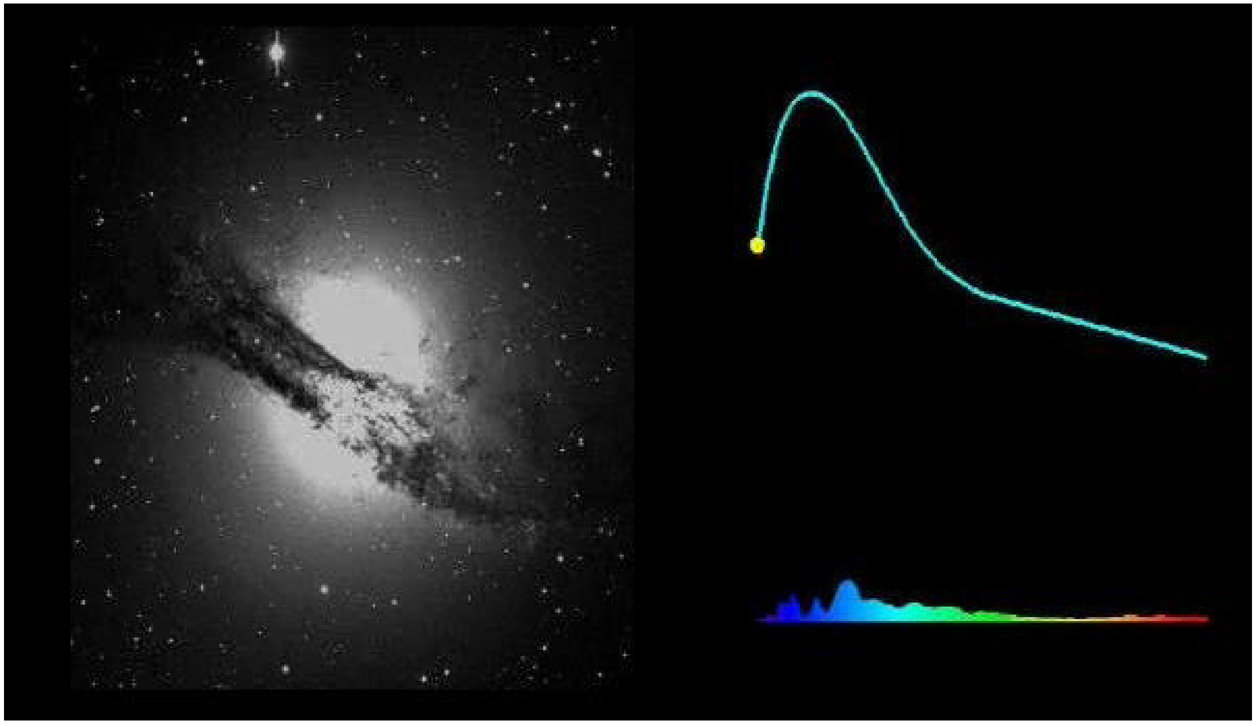
Type Ia Supernovae

- Characterized by no Hydrogen, but with Silicon
- Progenitor C/O White Dwarf accreting from companion
- Just before Chandrasekhar mass, thermonuclear runaway

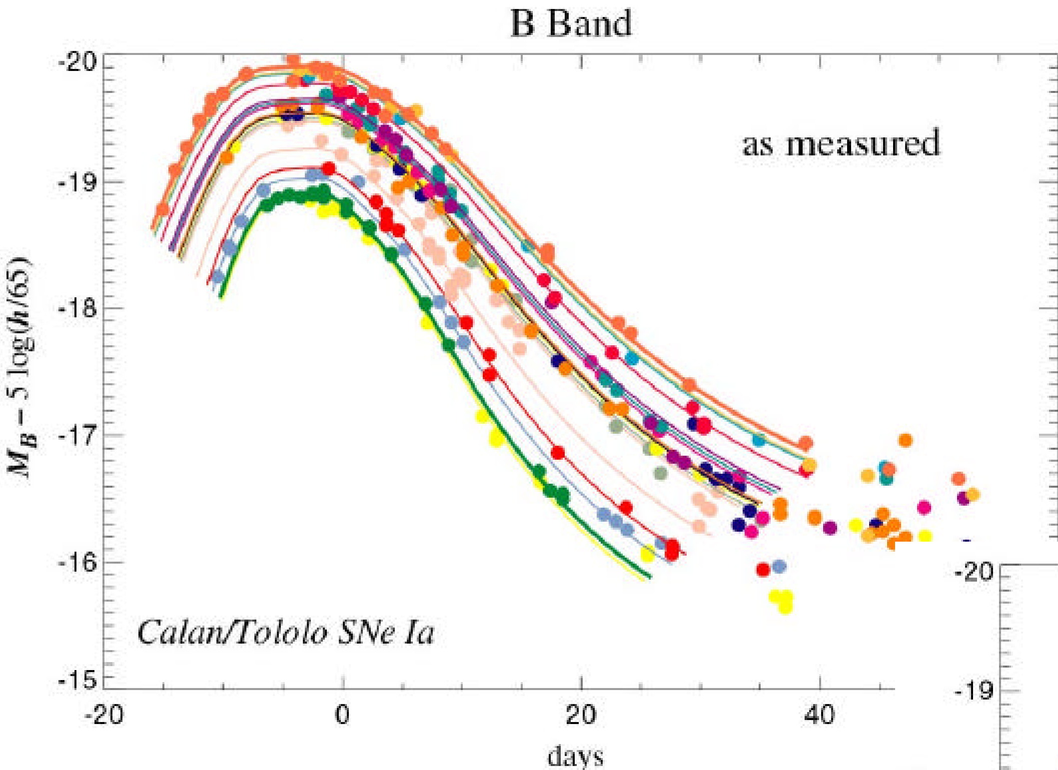
Standard explosion from nuclear physics

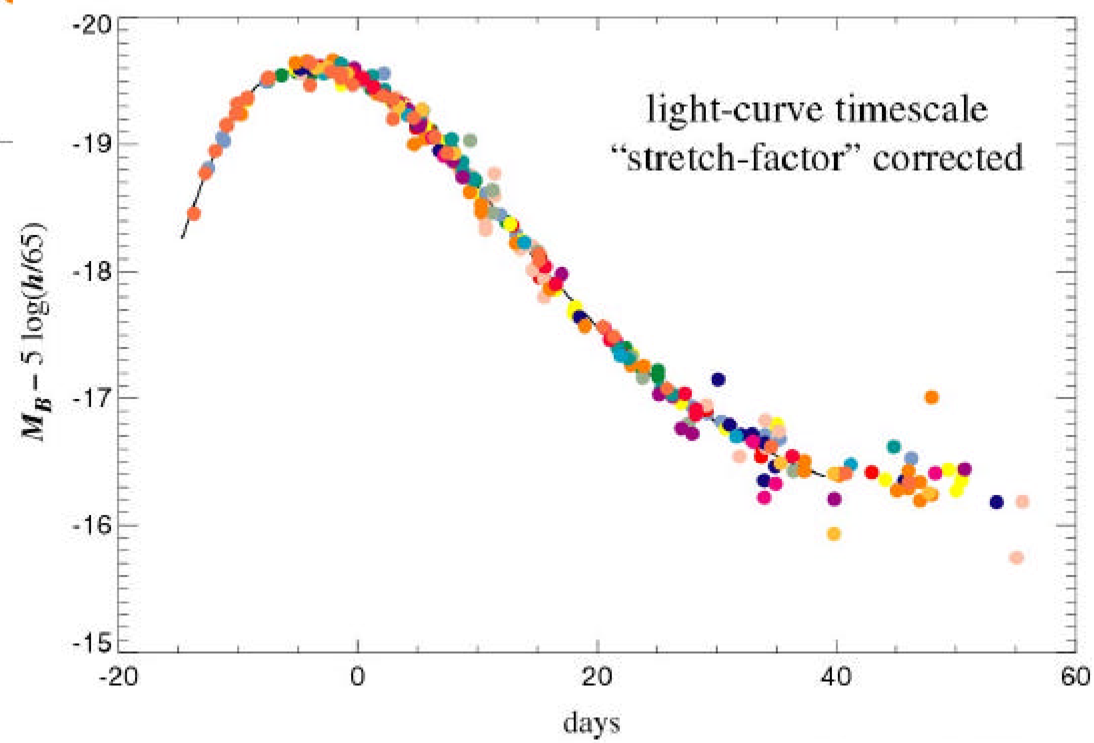
Insensitive to initial conditions:
“stellar amnesia”
Höflich, Gerardy, Linder, & Marion
astro-ph/0301334





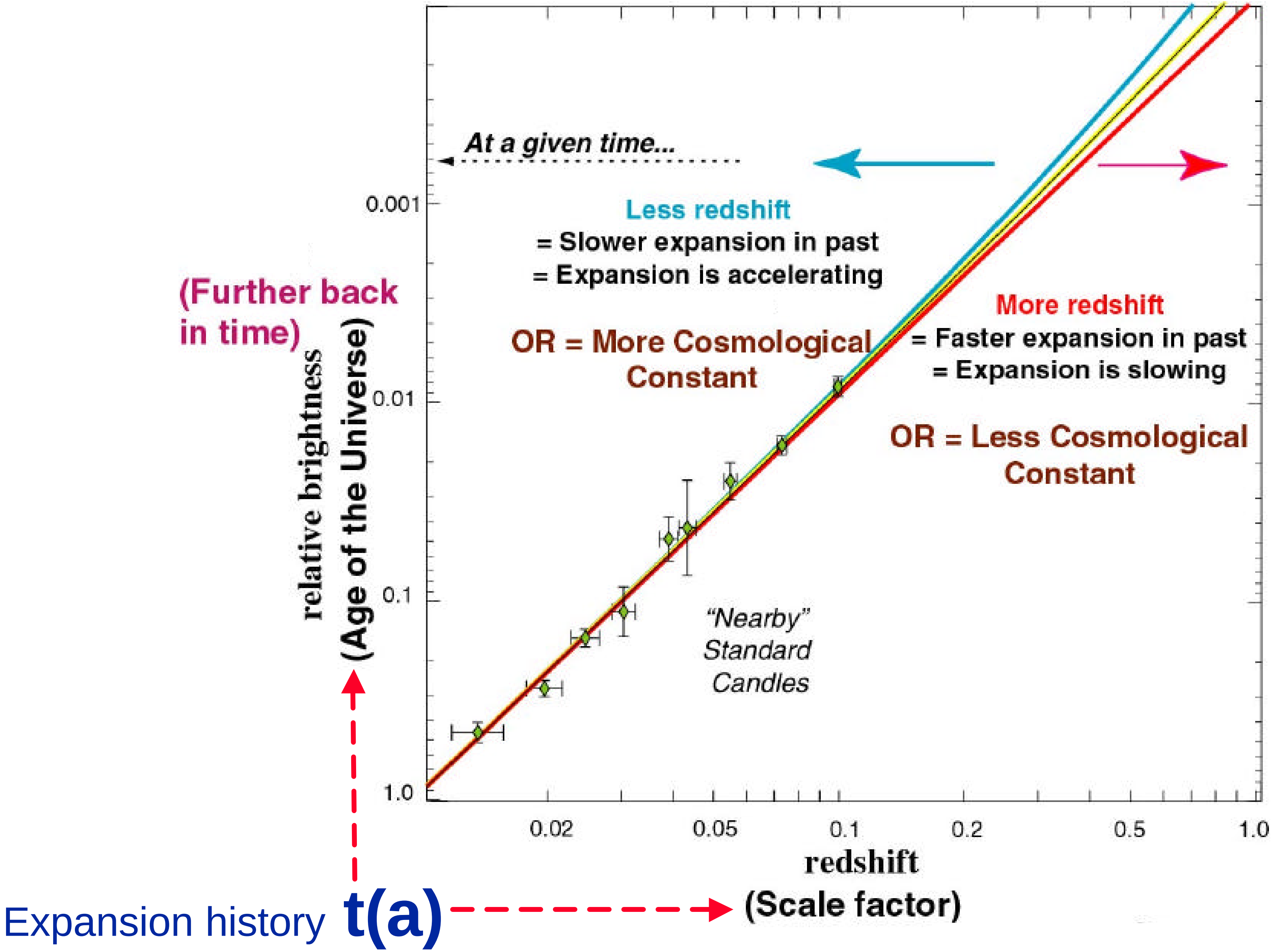
1 Parameter Family Homogeneity



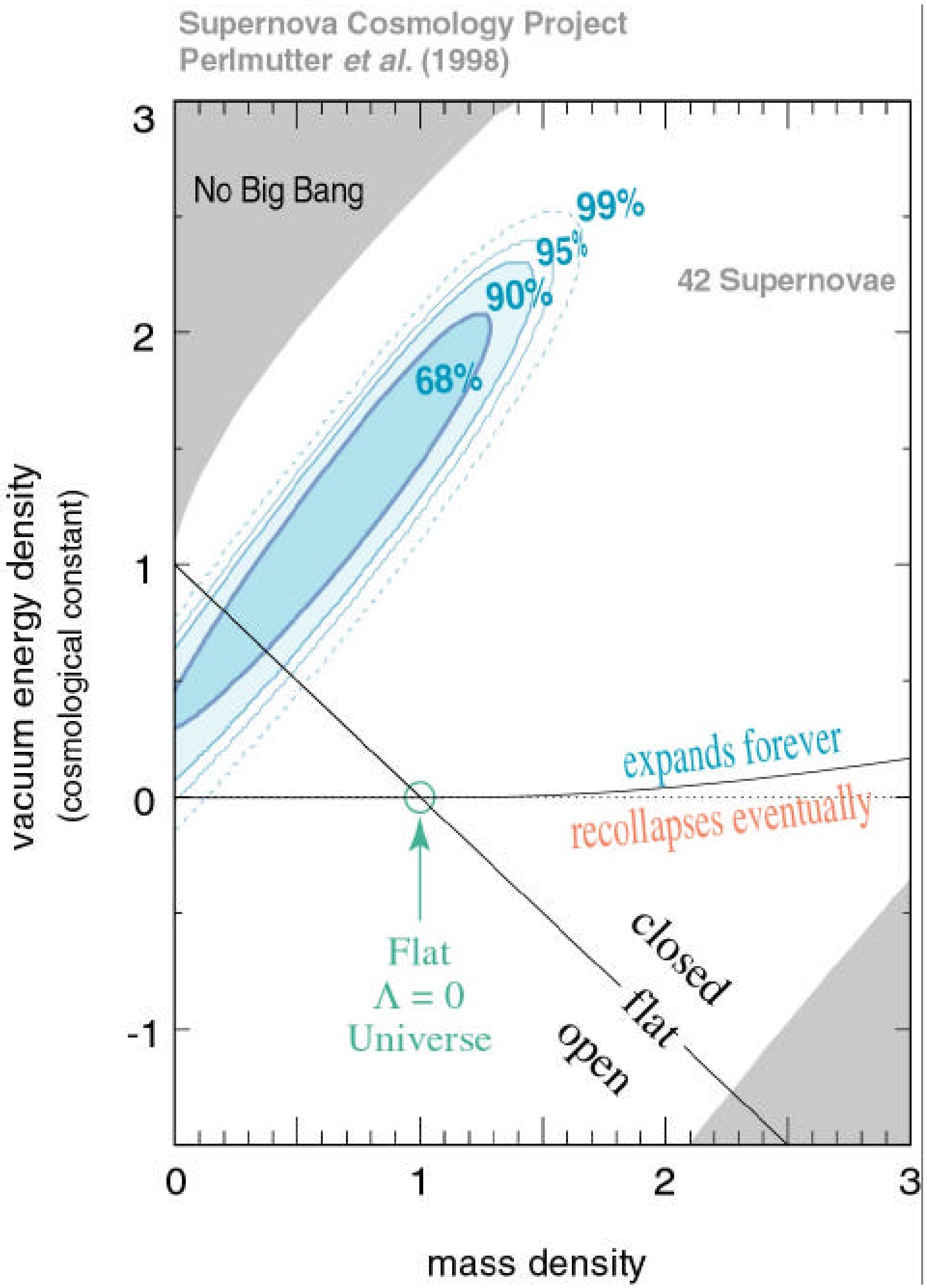


Kim, *et al.* (1997)

Hubble diagram – low z



Supernova Cosmology

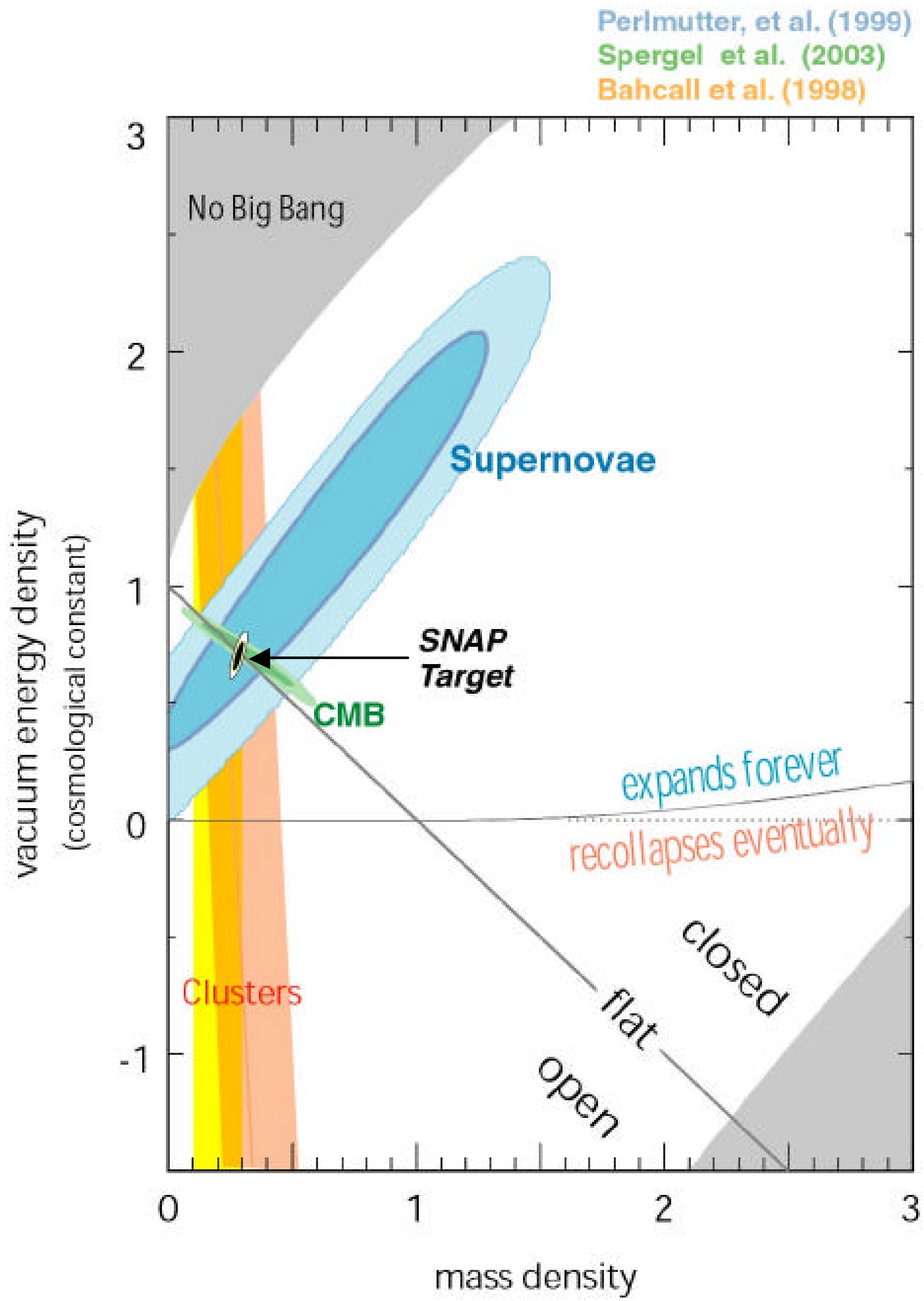


In flat universe:

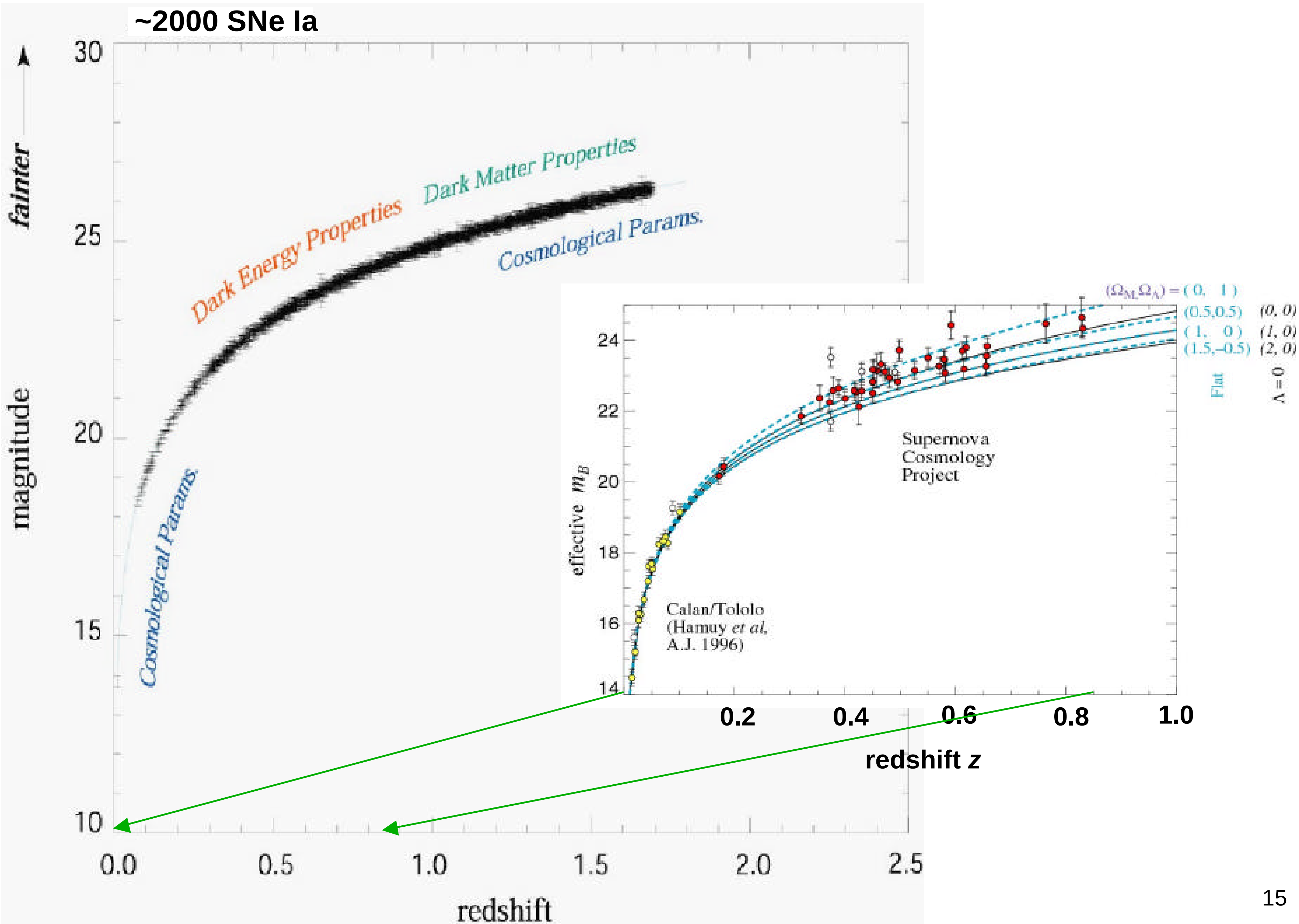
Ω_M=0.28 [±.085 stat][±.05 syst]

Prob. of fit to Λ=0 universe: 1%

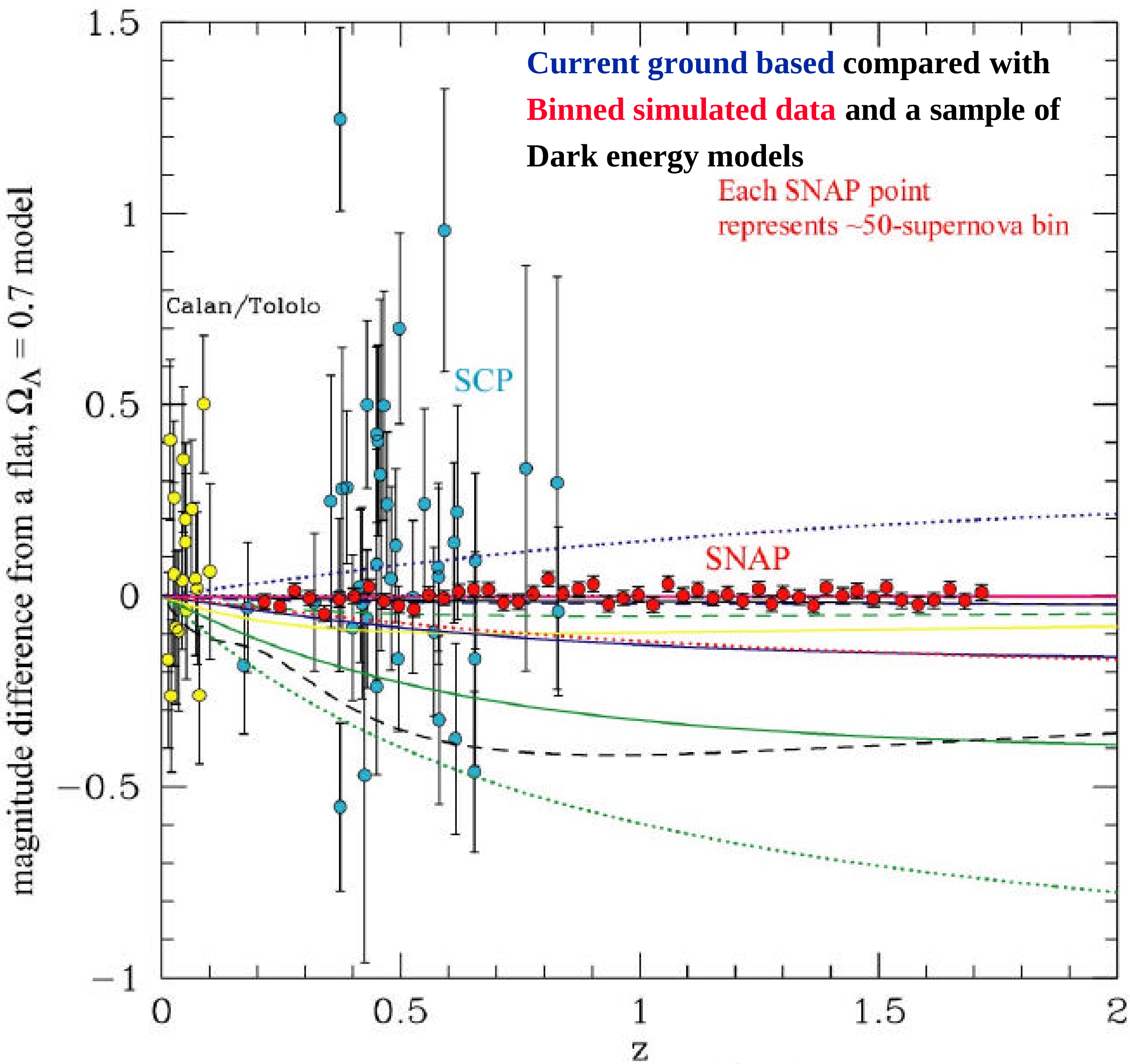
SNAP: The Third Generation



Hubble Diagram

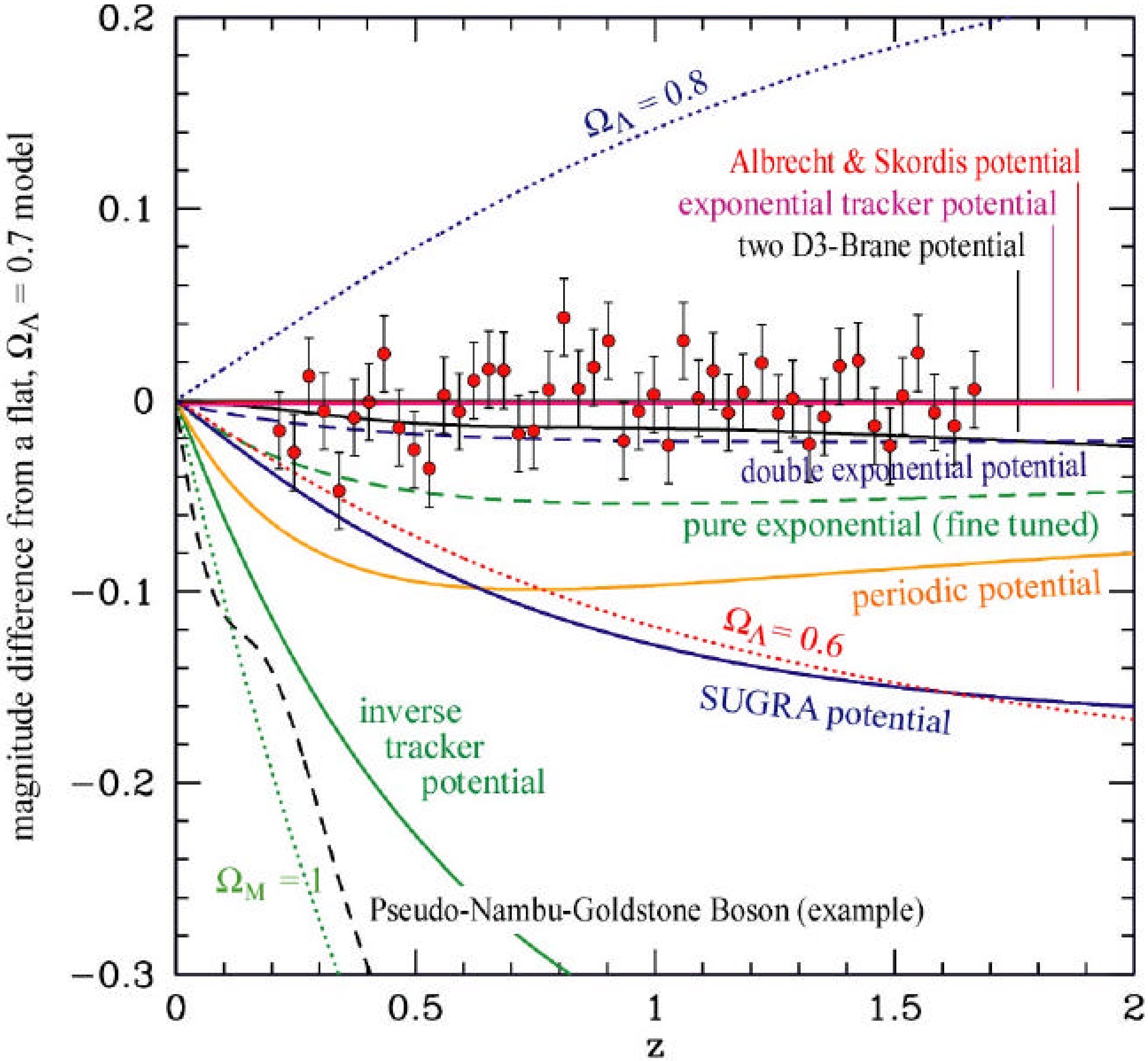


Dark Energy Exploration with SNAP



based on
Weller & Albrecht (2001)

Probing Dark Energy Models



based on

Weller & Albrecht (2001)

Mission Design

- **~2 m aperture telescope**

  Reach very distant SNe.
- **1 degree mosaic camera, ½ billion pixels**

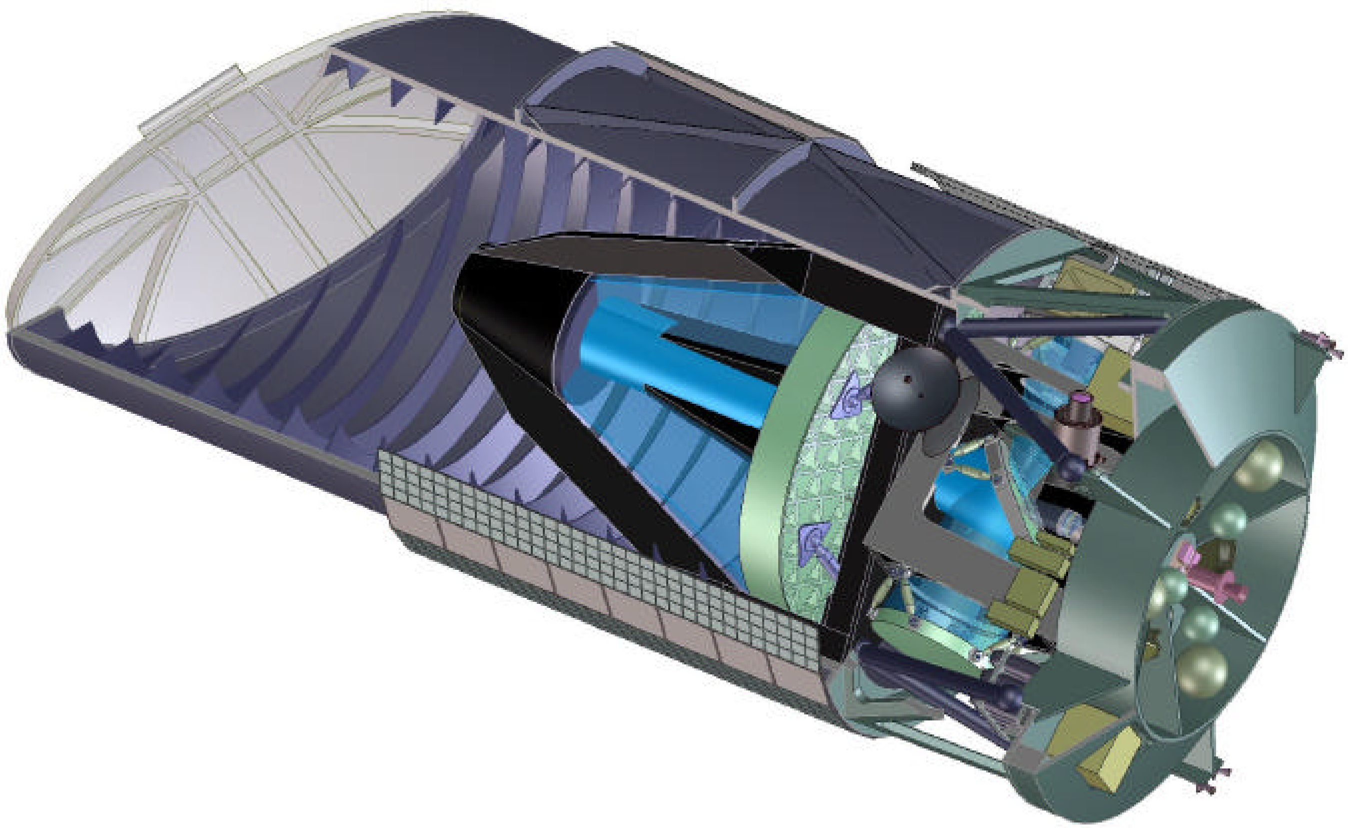
  Efficiently study large numbers of SNe.
- **0.35 – 1.7 mm spectrograph**

  Analyze in detail each SN.

Dedicated instrument designed to repeatedly observe an area of sky.

Essentially no moving parts.

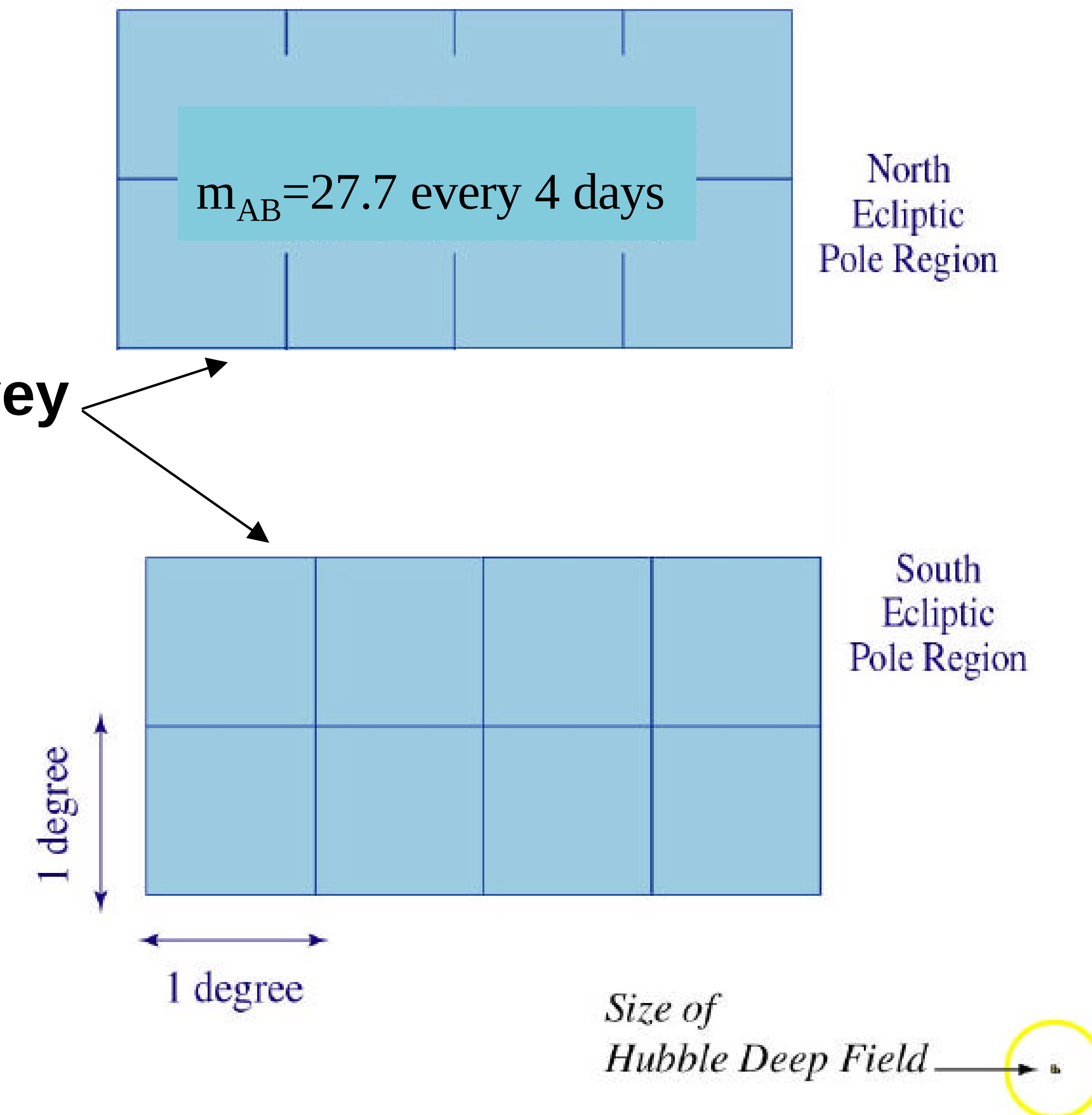
3 year operation for experiment (lifetime open ended).



SNAP Survey Fields

15 sq.deg. deep survey

+ ~300 sq.deg. wide weak lensing survey



Co-added images: m_{AB} = 31.0 !